Renewable and Sustainable Energy Reviews 16 (2012) 1496–1507

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Wind energy potential assessment for the Sultanate of Oman

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ARTICLE INFO

Article history:
Received 1 April 2010
Accepted 8 March 2011
Available online 16 January 2012

Keywords:
Wind energy
Wind power generation
Wind resource assessment

ABSTRACT

Wind data analysis for the Sultanate of Oman is carried out in this study. The results are presented mainly in the form of contour maps, in addition to tabulated data and figures for average wind speed and direction as well as wind availability and power density spanning a period of ten years. The analysis covers diurnal, seasonal and height variations on wind parameters. The data used in the analysis were obtained from NASA Langley Research Center. This analysis provides a needed reference for the spatial distribution of wind characteristics for the whole of Oman from which possible locations for the deployment of wind-based energy conversion systems may be identified.

Contents

1. Introduction

Utilization of wind energy in generation of electricity is growing at a fast rate due to the continued improvements in technology that make wind turbines cheaper and more efficient resulting in reduction of the overall cost of generation per kWh. In addition, wind energy is a clean, plentiful and sustainable energy source [1–4]. It does not create pollution like fossil or nuclear fuels and is inexhaustible. However, it is intermittent, leading to its unreliability. It is subject to diurnal, seasonal and yearly variations in addition to its dependence on height above the ground and nature of the surrounding terrain. This makes wind data analysis and accurate wind energy potential assessment prior to the deployment of any wind-based energy conversion system (WECS) an essential task [5,6].

There are no maps showing wind speed data throughout Oman. The usual practice is to draw such maps using ground stations meteorological data. However, most of the time, the locations of these stations are not suitable for wind energy conversion systems [1]. Furthermore, there are large areas of Oman, which lie between latitude 16°40′N and 26°20′N and longitudes 51°50′E and 59°40′E, with no meteorological stations. In this study, Oman is divided into thirty three sectors (see Fig. 1). The wind parameters over each of these sectors are obtained from the Atmospheric Science Data Center (ASDC) at NASA Langley Research Center [7].

The main objective of this work is to provide a guide for determining proper sites and other data essential in designing and deploying wind energy power generation systems and farms. These data are presented in the form of contour maps for wind speed and direction. These provide a needed reference for the spatial distribution of wind characteristics for the whole of Oman. Wind availability analysis is presented in terms of frequency at which the wind speed remained in specified intervals. Wind power density spatial distribution is computed as well. The data covers diurnal, monthly and annual wind parameters variations.

A description of the data used and the corresponding sectors is given in Section 2. The results obtained are discussed in Section 3 followed by conclusions in Section 4.

2. Data and sectors description

The data used in this study were obtained from NASA Langley Research Center [7]. The data are averaged over a period spanning ten years. Table 1 shows the geographical details of the centers of

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doi:10.1016/j.rser.2011.12.011

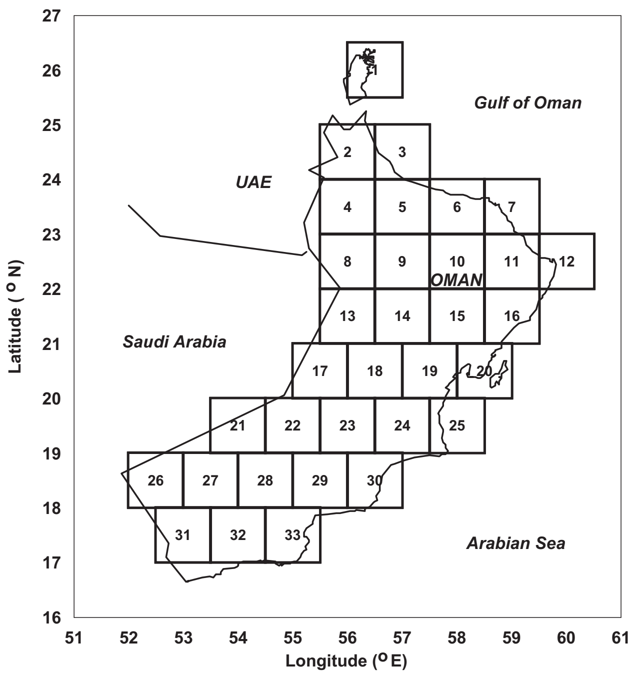


Fig. 1. Sectors considered in the study.

the selected sectors in Oman. Each sector spans by 1° latitude and longitude. Monthly averaged wind speeds at 50 m above the surface of the earth are presented in Table 2. Table 3 provides the monthly averaged wind direction at 50 m above the surface of the earth to reflect the seasonal variations. As wind speed varies with altitude, Table 4 summarizes the annual average wind speed at 10, 50, 100 and 150 m above the surface of the earth.

Table 1
Coordinates of centers of sectors considered in the study.

Sector	Latitude (°N)	Longitude (°E)	Sector	Latitude (°N)	Longitude (°E)
1	56.50	26.00	18	56.50	20.50
2	56.00	24.50	19	57.50	20.50
3	57.00	24.50	20	58.50	20.50
4	56.00	23.50	21	54.00	19.50
5	57.00	23.50	22	55.00	19.50
6	58.00	23.50	23	56.00	19.50
7	59.00	23.50	24	57.00	19.50
8	56.00	22.50	25	58.00	19.50
9	57.00	22.50	26	52.50	18.50
10	58.00	22.50	27	53.50	18.50
11	59.00	22.50	28	54.50	18.50
12	60.00	22.50	29	55.50	18.50
13	56.00	21.50	30	56.50	18.50
14	57.00	21.50	31	53.00	17.50
15	58.00	21.50	32	54.00	17.50
16	59.00	21.50	33	55.00	17.50
17	55.50	20.50			

3. Results and discussion

Contour maps for monthly averaged wind speed and wind direction map at 50 m above the surface of the earth are displayed in Fig. 2 . It is observed that the wind speed is in general higher in the coastal regions and in particular in the south east. The maximum wind speeds are observed in this region in June, July and August

Table 2
Monthly averaged wind speed (m/s) at 50 m above the surface of the earth.

Sector	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	5.04	5.66	5.47	5.53	6.11	5.99	5.81	5.71	5.58	5.00	4.47	5.03
2	4.50	5.12	4.87	4.80	5.47	5.47	5.35	5.15	4.92	4.24	3.86	4.42
3	4.47	5.03	4.80	4.75	5.47	5.53	5.56	5.39	5.14	4.22	3.83	4.38
4	4.34	4.87	4.62	4.50	5.21	5.38	5.47	5.15	4.84	3.98	3.68	4.24
5	4.28	4.75	4.53	4.42	5.28	5.56	5.83	5.50	5.08	3.94	3.61	4.17
6	4.30	4.83	4.65	4.63	5.59	5.99	6.65	6.40	5.66	4.01	3.57	4.18
7	4.34	4.91	4.76	4.84	5.91	6.43	7.46	7.29	6.23	4.09	3.52	4.20
8	4.36	4.73	4.51	4.40	5.13	5.52	5.92	5.42	5.04	3.95	3.69	4.26
9	4.17	4.47	4.25	4.13	5.17	5.78	6.39	5.83	5.25	3.83	3.50	4.05
10	4.26	4.62	4.46	4.47	5.74	6.45	7.33	6.79	6.04	4.08	3.58	4.17
11	4.36	4.76	4.68	4.80	6.31	7.12	8.27	7.75	6.82	4.33	3.66	4.28
12	4.42	4.83	4.74	5.01	6.63	7.48	8.69	8.07	7.07	4.42	3.72	4.38
13	4.42	4.70	4.46	4.34	5.22	5.95	6.66	5.96	5.33	4.01	3.78	4.38
14	4.22	4.42	4.13	4.05	5.28	6.28	7.19	6.44	5.53	3.89	3.58	4.17
15	4.41	4.58	4.34	4.42	5.95	7.02	8.15	7.36	6.30	4.17	3.77	4.37
16	4.59	4.74	4.55	4.78	6.63	7.76	9.10	8.27	7.08	4.45	3.95	4.57
17	4.57	4.95	4.63	4.54	5.34	6.30	7.12	6.24	5.49	4.25	3.99	4.63
18	4.51	4.76	4.42	4.34	5.47	6.68	7.69	6.79	5.70	4.18	3.93	4.57
19	4.44	4.58	4.19	4.17	5.61	7.06	8.25	7.33	5.92	4.11	3.86	4.50
20	4.73	4.70	4.29	4.45	6.24	7.70	9.10	8.11	6.46	4.28	4.12	4.78
21	4.87	5.20	4.80	4.67	5.48	6.70	7.56	6.67	5.74	4.44	4.26	4.93
22	4.75	5.00	4.62	4.57	5.67	7.13	8.22	7.24	5.96	4.42	4.18	4.86
23	4.80	4.93	4.54	4.59	6.06	7.74	8.98	8.00	6.33	4.49	4.25	4.90
24	4.88	4.87	4.45	4.63	6.45	8.34	9.75	8.77	6.70	4.55	4.32	4.94
25	5.18	4.90	4.36	4.63	6.74	8.69	10.3	9.24	6.85	4.50	4.59	5.25
26	5.23	5.51	4.99	4.90	5.39	6.58	7.18	6.56	5.80	4.66	4.63	5.18
27	5.16	5.34	4.86	4.76	5.53	6.99	7.84	7.10	5.97	4.59	4.54	5.17
28	5.09	5.17	4.73	4.62	5.68	7.40	8.50	7.65	6.14	4.53	4.46	5.17
29	5.15	5.12	4.71	4.74	6.16	8.11	9.41	8.48	6.55	4.63	4.53	5.23
30	5.33	5.20	4.80	5.09	6.98	9.11	10.5	9.61	7.21	4.93	4.74	5.36
31	5.36	5.28	4.76	4.75	5.74	7.75	8.86	8.13	6.33	4.67	4.72	5.39
32	5.51	5.28	4.76	4.76	6.11	8.41	9.69	8.90	6.65	4.71	4.8	5.55
33	5.69	5.33	4.80	4.91	6.62	9.19	10.6	9.78	7.08	4.83	4.98	5.72
Minimum	4.17	4.42	4.13	4.05	5.13	5.38	5.35	5.15	4.84	3.83	3.50	4.05
Maximum	5.69	5.66	5.47	5.53	6.98	9.19	10.60	9.78	7.21	5.00	4.98	5.72
Average	4.72	4.94	4.62	4.64	5.83	6.96	7.86	7.18	6.02	4.34	4.08	4.71

Table 3
Monthly averaged wind direction (°) at 50 m above the surface of the earth.

Sector	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Minimum	Maximum	Average
1	350	355	328	317	318	321	328	333	338	344	345	348	317	355	335
2	93	13	317	308	304	299	290	278	273	275	278	282	13	317	251
3	6	15	305	296	293	286	273	256	249	249	254	258	6	305	228
4	93	13	317	308	304	299	290	278	273	275	278	282	13	317	251
5	6	15	305	296	293	286	273	256	249	249	254	258	6	305	228
6	8	15	316	286	275	266	255	241	236	236	239	242	8	316	218
7	15	16	347	257	222	207	200	195	195	195	195	194	15	347	187
8	38	46	47	37	161	151	242	149	152	156	153	147	37	242	123
9	44	52	57	45	212	199	202	198	197	193	188	181	44	212	147
10	44	51	59	68	205	197	200	198	197	194	189	184	44	205	149
11	45	48	68	139	184	191	195	195	196	196	194	191	45	196	154
12	45	48	68	139	184	191	195	195	196	196	194	191	45	196	154
13	38	46	47	37	161	151	242	149	152	156	153	147	37	242	123
14	44	52	57	45	212	199	202	198	197	193	188	181	44	212	147
15	44	51	59	68	205	197	200	198	197	194	189	184	44	205	149
16	45	48	68	139	184	191	195	195	196	196	194	191	45	196	154
17	50	59	75	97	142	173	191	194	192	189	183	177	50	194	144
18	64	74	93	119	157	179	193	196	196	193	189	184	64	196	153
19	68	79	99	126	162	181	193	197	197	195	191	186	68	197	156
20	64	73	91	117	162	183	195	198	198	197	193	188	64	198	155
21	50	59	75	97	142	173	191	194	192	189	183	177	50	194	144
22	50	59	75	97	142	173	191	194	192	189	183	177	50	194	144
23	64	74	93	119	157	179	193	196	196	193	189	184	64	196	153
24	68	79	99	126	162	181	193	197	197	195	191	186	68	197	156
25	64	73	91	117	162	183	195	198	198	197	193	188	64	198	155
26	68	81	110	132	150	168	182	186	187	185	179	173	68	187	150
27	70	83	110	133	153	171	185	189	190	188	182	177	70	190	153
28	76	89	113	137	163	182	193	198	198	196	192	187	76	198	160
29	76	89	113	137	163	182	193	198	198	196	192	187	76	198	160
30	76	86	106	131	160	179	190	195	196	194	190	185	76	196	157
31	70	83	110	133	153	171	185	189	190	188	182	177	70	190	153
32	76	89	113	137	163	182	193	198	198	196	192	187	76	198	160
33	76	89	113	137	163	182	193	198	198	196	192	187	76	198	160

Table 4
Annual average wind speed (m/s) at 10, 50, 100 and 150 m above the surface of the earth.

Sector	10 m	50 m	100 m	150 m	Sector	10 m	50 m	100 m	150 m
1	3.82	5.44	6.34	6.93	18	3.69	5.25	6.12	6.69
2	3.40	4.84	5.64	6.17	19	3.74	5.34	6.22	6.80
3	4.15	4.88	5.23	5.44	20	4.90	5.75	6.16	6.42
4	3.29	4.68	5.46	5.97	21	3.82	5.44	6.34	6.93
5	3.33	4.74	5.52	6.04	22	3.90	5.55	6.47	7.07
6	3.54	5.04	5.87	6.42	23	4.07	5.81	6.76	7.39
7	4.54	5.33	5.71	5.95	24	4.25	6.06	7.06	7.72
8	3.33	4.74	5.52	6.04	25	5.34	6.28	6.73	7.01
9	3.32	4.73	5.52	6.03	26	3.89	5.55	6.46	7.06
10	3.62	5.17	6.02	6.58	27	3.97	5.65	6.58	7.20
11	3.93	5.60	6.52	7.13	28	4.04	5.76	6.71	7.34
12	4.93	5.79	6.21	6.47	29	4.26	6.07	7.07	7.73
13	3.46	4.93	5.75	6.28	30	4.62	6.59	7.67	8.39
14	3.46	4.93	5.75	6.28	31	4.20	5.98	6.97	7.62
15	3.79	5.41	6.30	6.89	32	4.40	6.27	7.30	7.98
16	4.12	5.88	6.85	7.49	33	4.66	6.64	7.73	8.46
17	3.63	5.17	6.02	6.59					

Table 5
Annual average wind power density (W/m^2) at 10, 50, 100 and 150 m above the surface of the earth.

Sector	10 m	50 m	100 m	150 m	Sector	10 m	50 m	100 m	150 m
1	8.0	23.1	36.6	47.8	18	7.2	20.8	33.0	43.0
2	5.6	16.3	25.8	33.8	19	7.5	21.9	34.6	45.2
3	10.3	16.7	20.6	23.1	20	16.9	27.3	33.6	38.0
4	5.1	14.7	23.4	30.6	21	8.0	23.1	36.6	47.8
5	5.3	15.3	24.2	31.7	22	8.5	24.6	38.9	50.8
6	6.4	18.4	29.1	38.0	23	9.7	28.2	44.4	58.0
7	13.5	21.8	26.8	30.3	24	11.0	32.0	50.6	66.1
8	5.3	15.3	24.2	31.7	25	21.9	35.6	43.8	49.5
9	5.3	15.2	24.2	31.5	26	8.5	24.6	38.8	50.6
10	6.8	19.9	31.4	41.0	27	9.0	25.9	41.0	53.7
11	8.7	25.2	39.8	52.1	28	9.5	27.5	43.4	56.8
12	17.2	27.9	34.4	38.9	29	11.1	32.1	50.8	66.4
13	6.0	17.2	27.3	35.6	30	14.2	41.1	64.9	84.9
14	6.0	17.2	27.3	35.6	31	10.7	30.7	48.7	63.6
15	7.8	22.8	35.9	47.0	32	12.2	35.4	55.9	73.0
16	10.1	29.2	46.2	60.4	33	14.5	42.1	66.4	87.0
17	6.9	19.9	31.4	41.1					

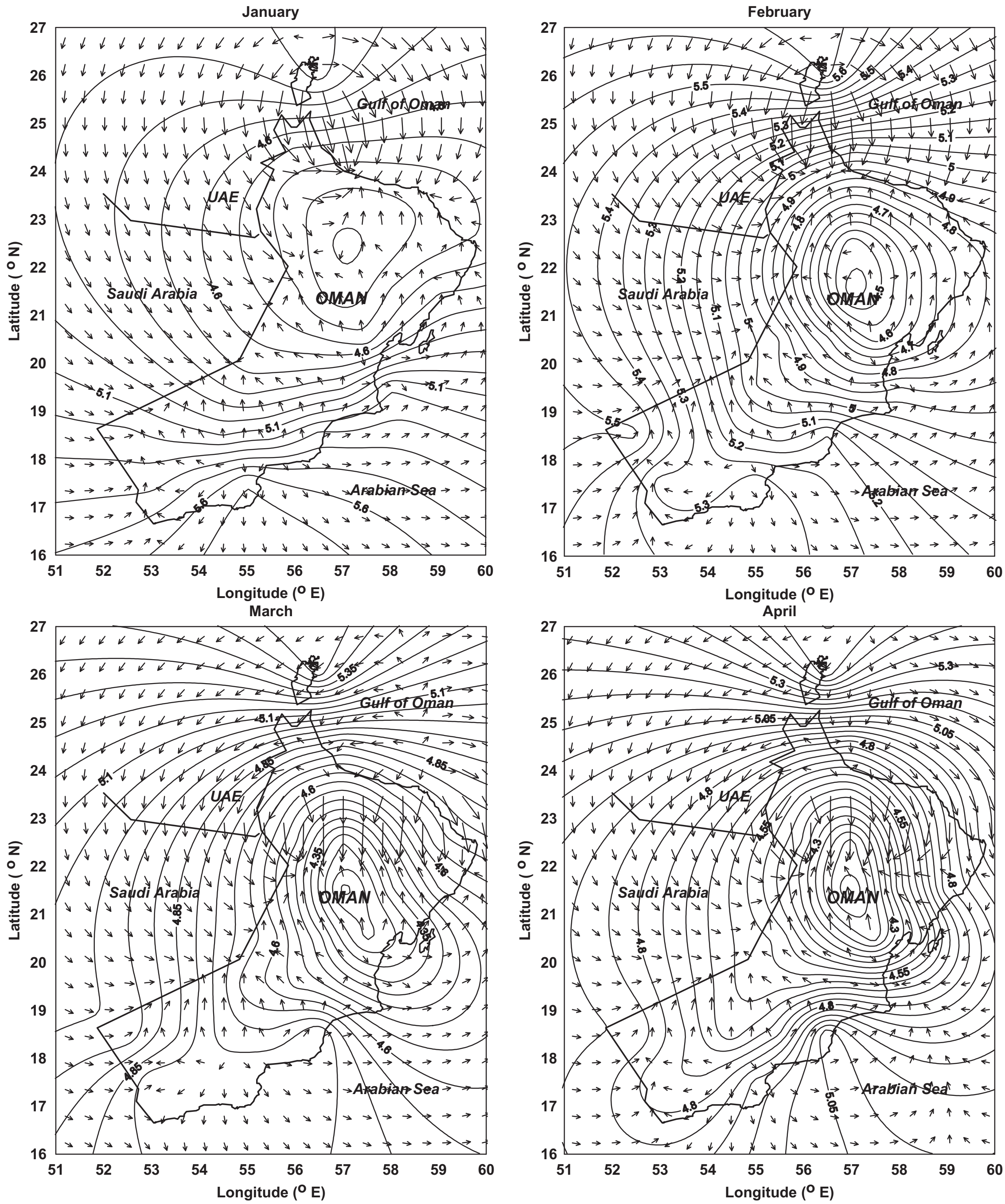


Fig. 2. Contour maps for monthly averaged wind speed (m/s) and direction at 50 m above the surface of the earth.

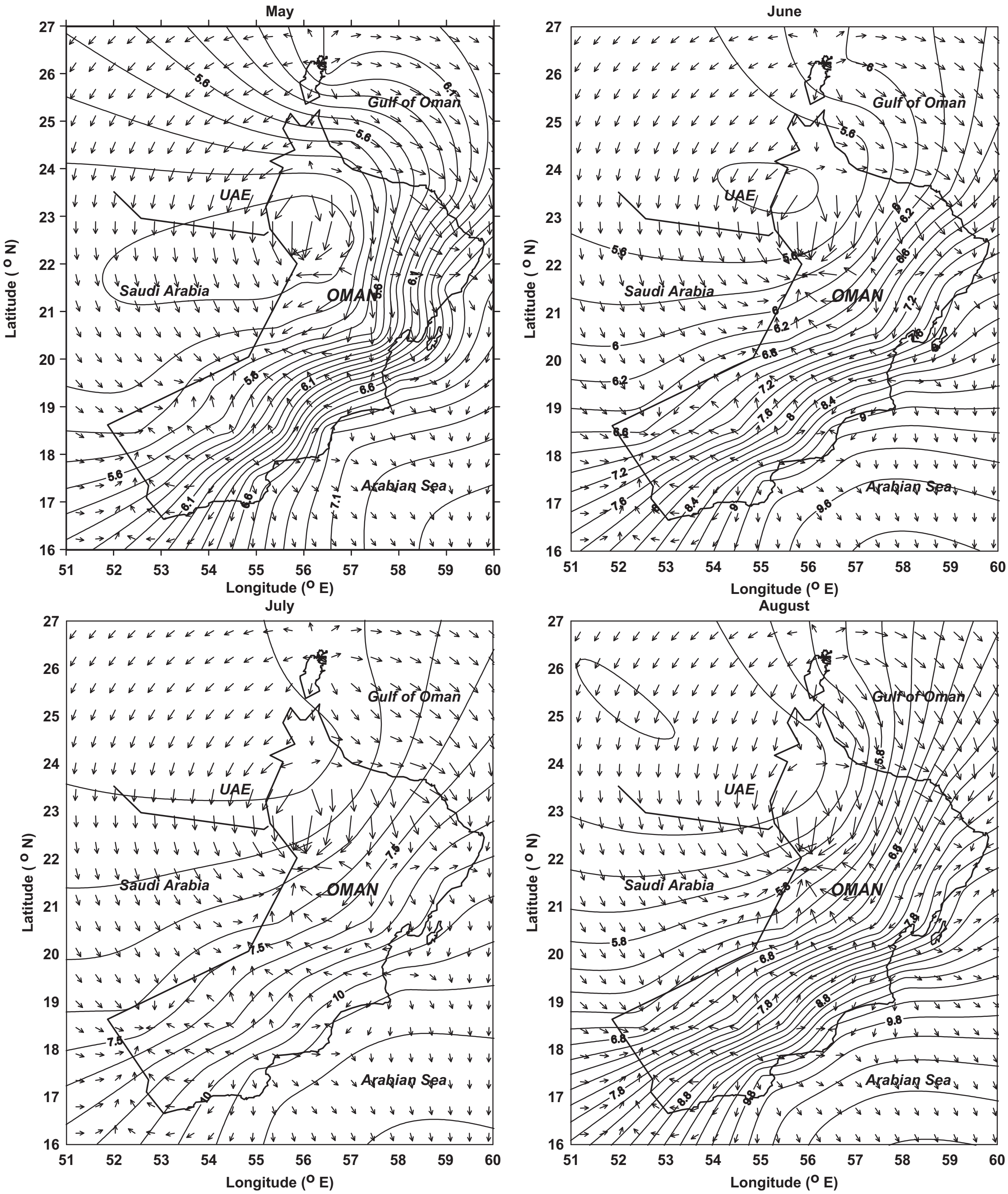


Fig. 2. (*continued*)

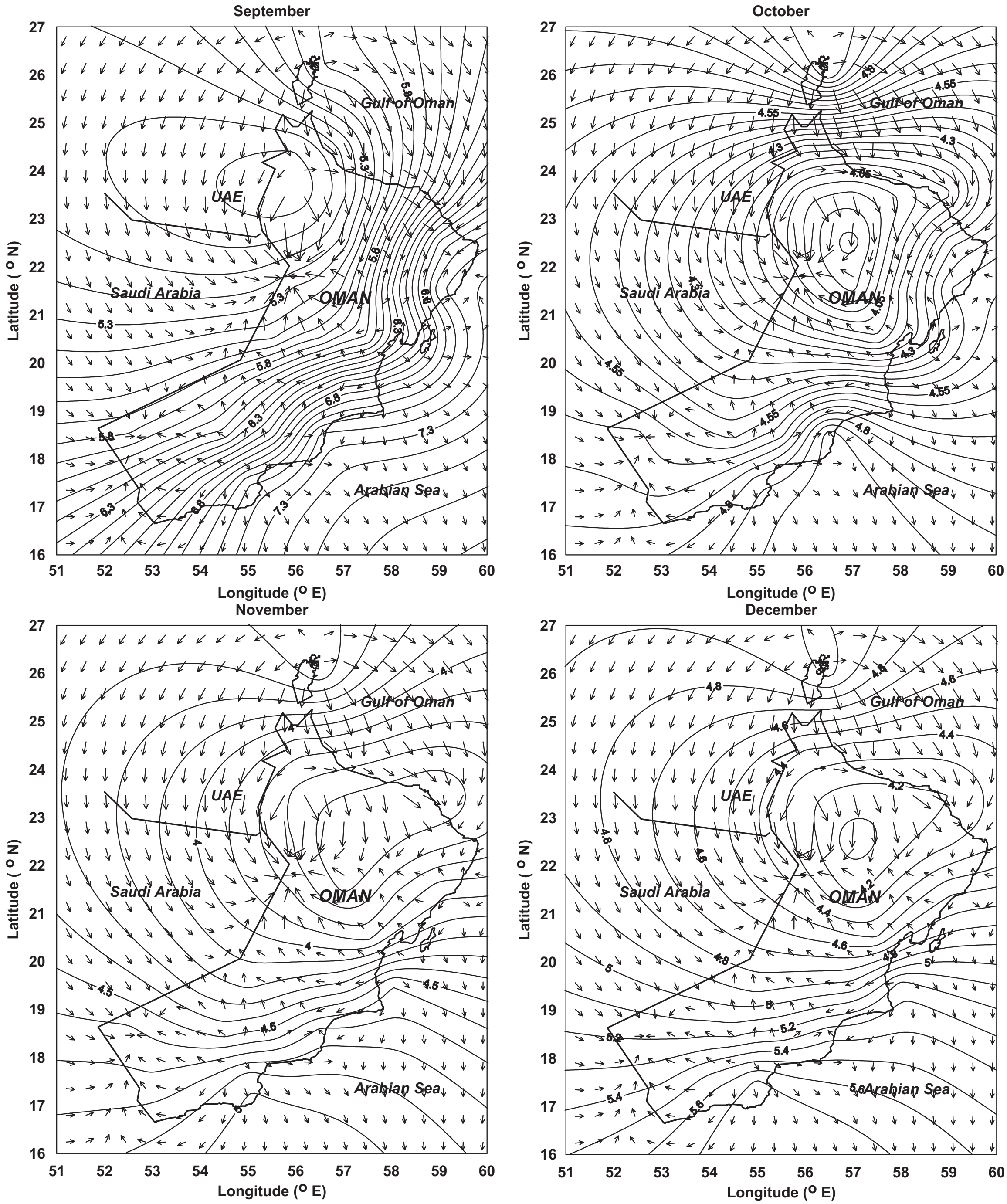


Fig. 2. (*continued*).

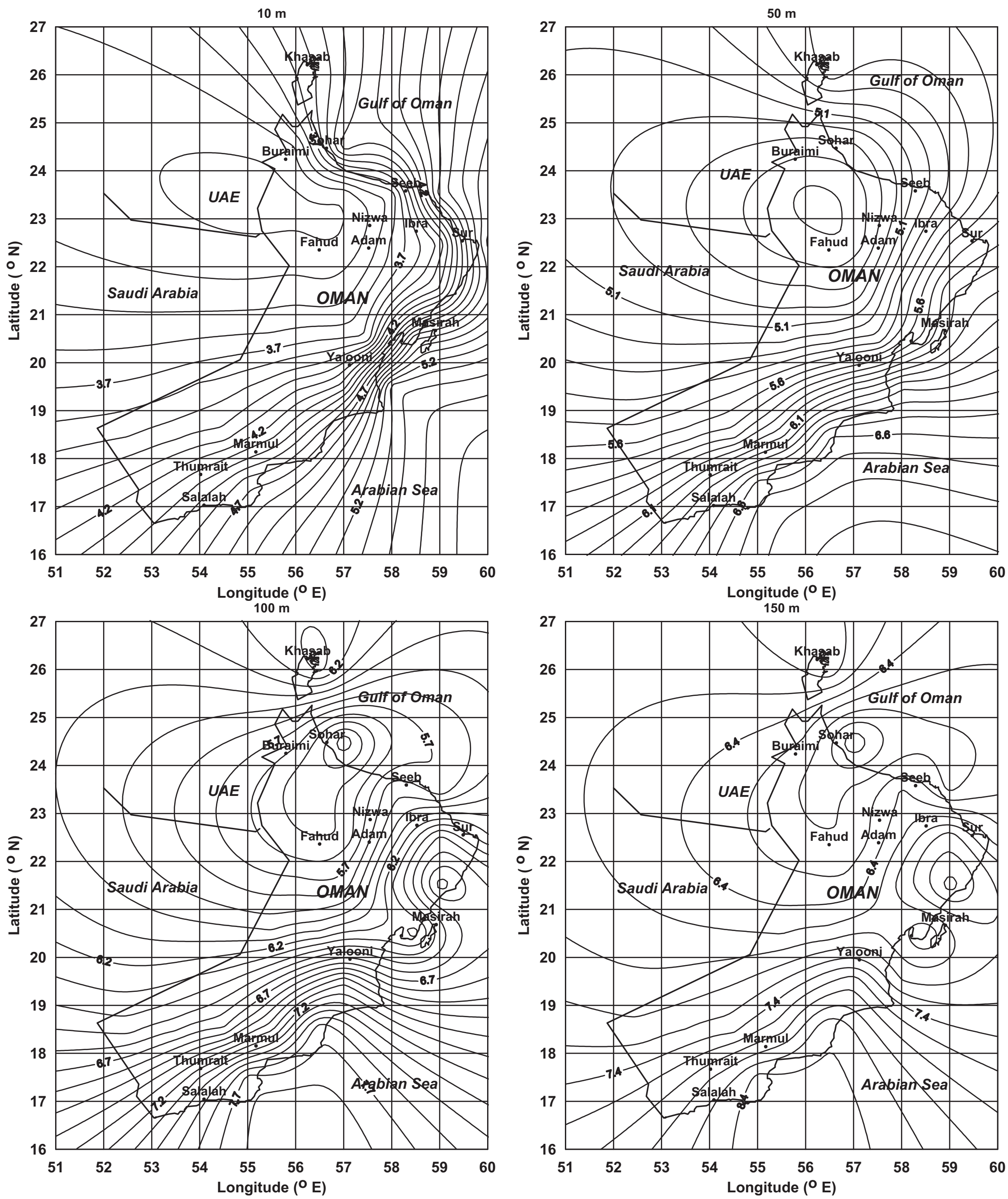


Fig. 3. Contour maps for annual average wind speed (m/s) at 10, 50, 100 and 150 m above the surface of the earth.

which may also be deduced from Table 2 which shows an average wind speed of 6.96, 7.86 and 7.18 m/s for the three months respectively. The annual average wind direction for each sector provides a guide for the orientation of horizontal axis wind turbines to be installed in these regions.

Contour maps for annual average wind speed (m/s) at 10, 50, 100 and 150 m above the surface of the earth are shown in Fig. 3. The general trend is that the wind speed increases with altitude as expected.

Fig. 4 shows the diurnal average wind speed at 50 m. It is interesting to note that the minima wind speed occur between 2:30 and 5:30 pm in all sectors. On the other hand, the maxima occur between 11:30 pm and 2:30 am.

Fig. 5 depicts the percent distribution of yearly averaged wind speed at 50 m in different bins. For about half the year the average wind speed lies between 3 and 6 m/s for all sectors. An annual average wind speed greater than four meters per second (m/s) is usually required for small wind electric turbines (less wind is required for water-pumping operations). On the other hand, a minimum average wind speed of 6 m/s is required for utility-scale wind power plants [1].

The power generated by a wind turbine P in watts may be obtained using [5]

$$P = \frac{1}{2} C_p N_g N_b \rho A V^3 \tag{1}$$

where C_p is the coefficient of performance, N_g is the generator efficiency, N_b is the gearbox/bearing efficiency, ρ is the air density in kg/m^3, A is the rotor swept area in m^2 and is given in terms of rotor diameter D by $\pi D^2/4$, V is the wind speed in m/s.

From (1), it is observed that the power available in the wind is proportional to the cube of its speed. This means that doubling the wind speed increases the available power by a factor of eight. Eq. (1) may be re-written as

$$P = \frac{1}{2} (\text{CF}) \rho A V^3 \tag{2}$$

where CF = $C_p N_g N_b$ is the capacity factor.

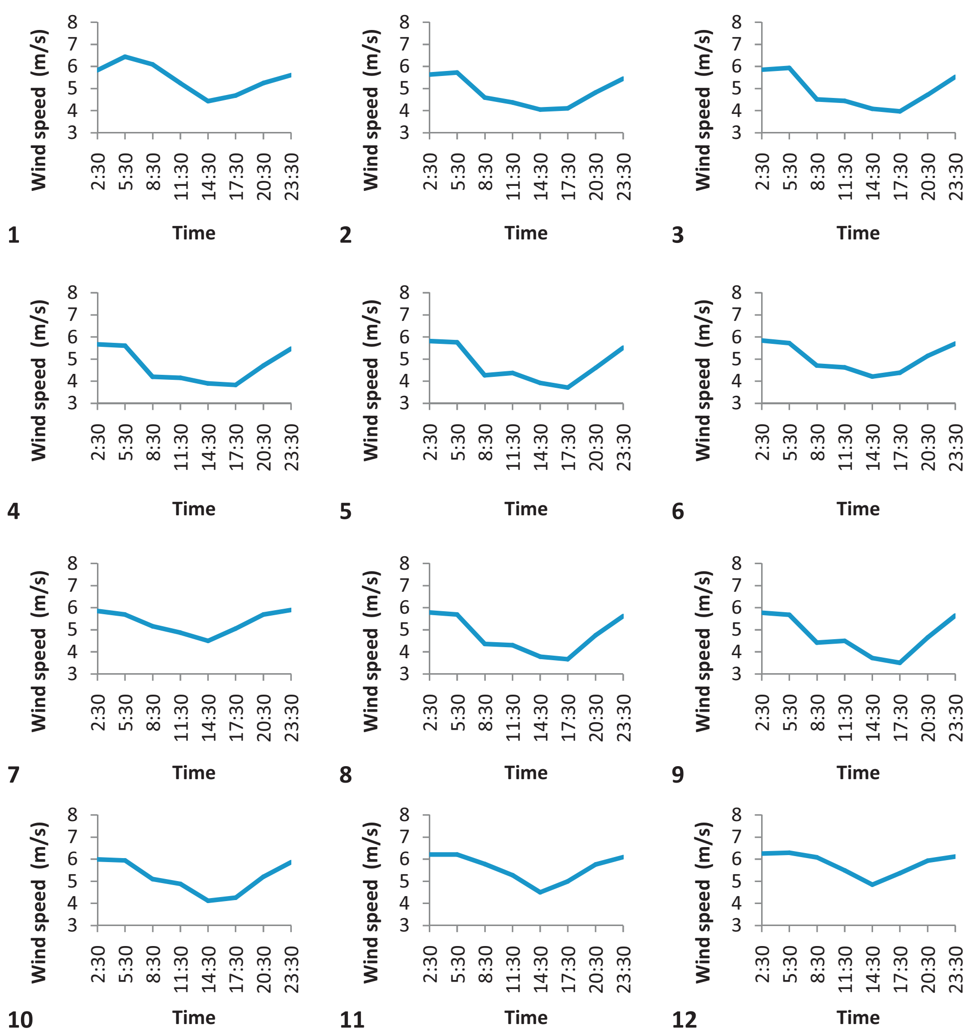


Fig. 4. Diurnal average wind speed at 50 m for sectors 1–12. Diurnal average wind speed at 50 m for sectors 13–24. Diurnal average wind speed at 50 m for sectors 25–33.

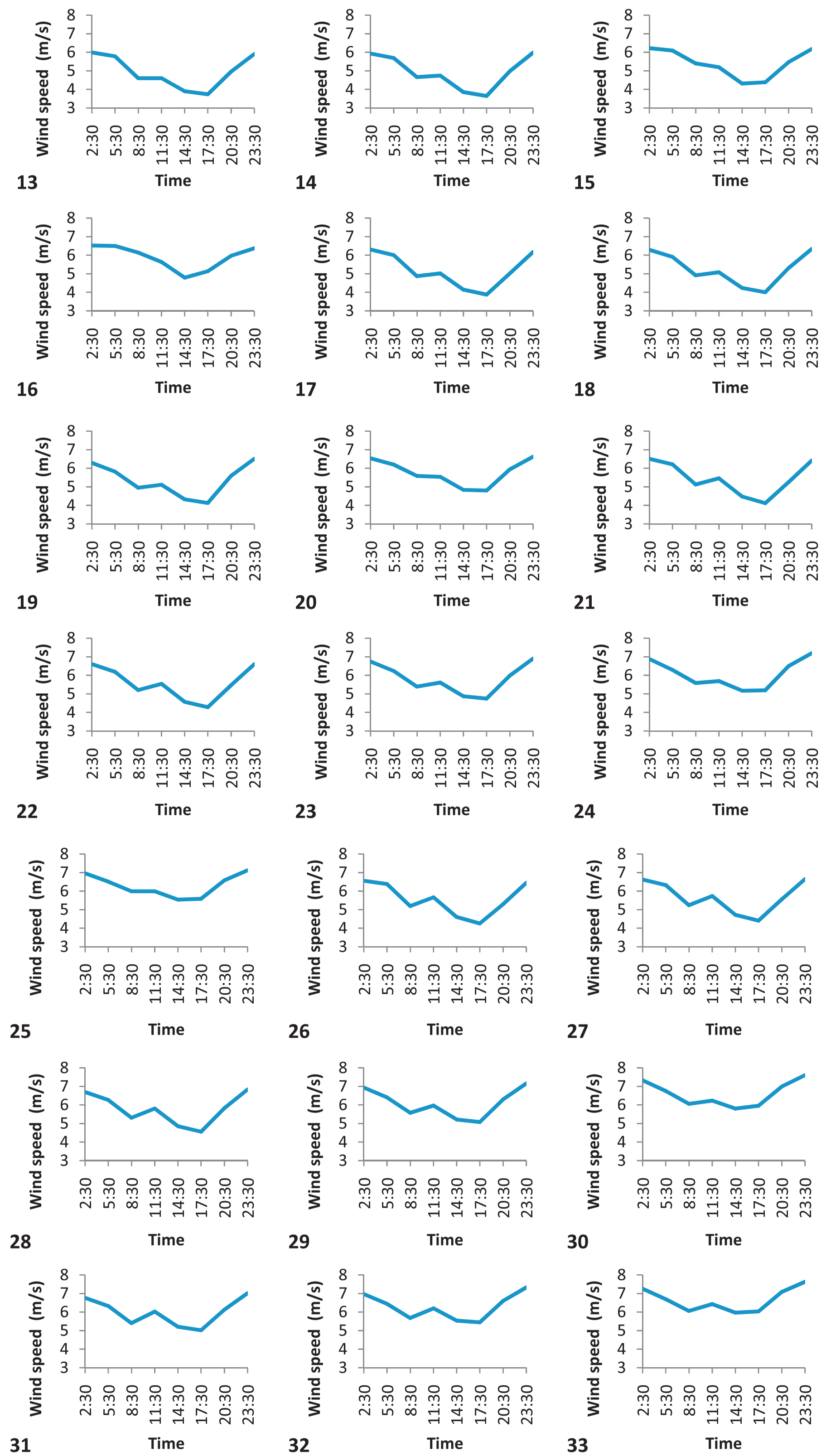


Fig. 4. (*continued*).

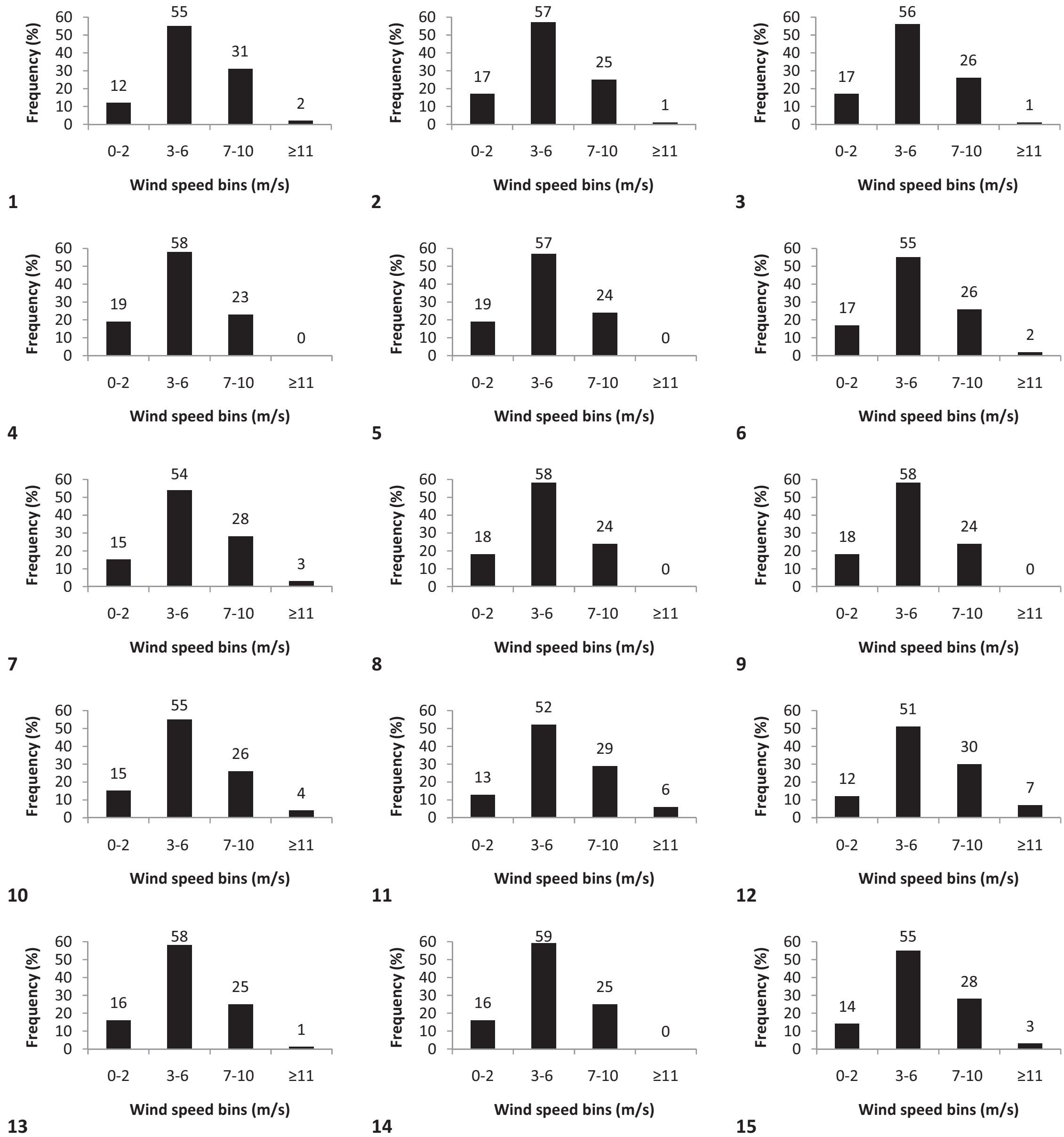


Fig. 5. Percent distribution of annual average wind speed at 50 m in different bins for sectors 1–15. Percent distribution of annual average wind speed at 50 m in different bins for sectors 16–33.

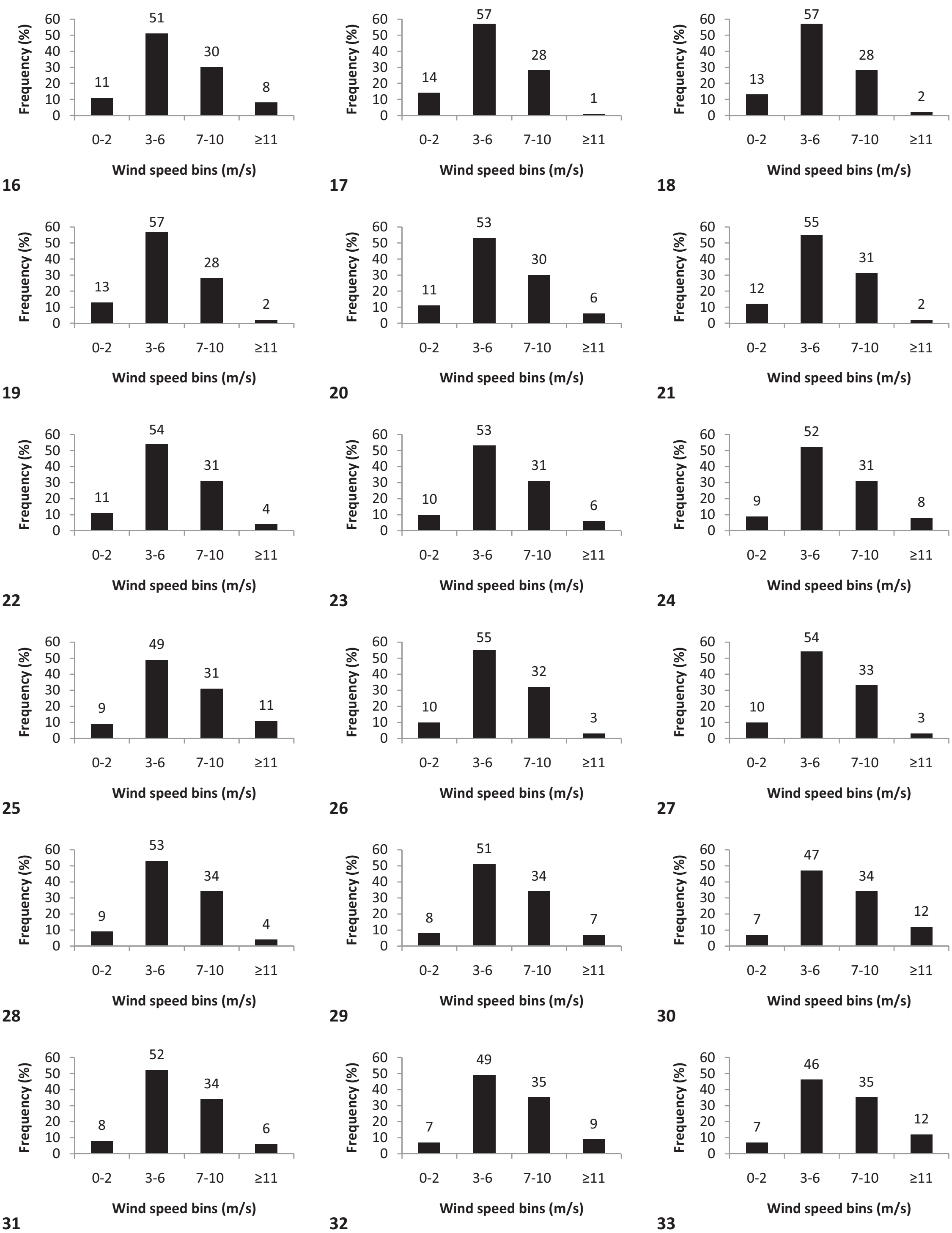


Fig. 5. (*continued*).

The capacity factor compares the actual production of a wind turbine over a given period of time with the amount of power the turbine would have produced if it had run at full capacity for the same amount of time. Capacity factors of 25–40% are common [1]. Based on a conservative estimate of 25% CF, the power density ($PD = (P/A) = 1/2(CF)\rho V^3$) is computed for thirty three sectors. Table 5 summarizes the annual average wind power density in W/m^2 for 10, 50, 100 and 150 m above the surface of the earth.

4. Conclusions

Wind resource assessment Oman was carried out in this study. The results are presented in the form of contour maps for average wind speed and direction as well as wind availability figures and wind power density tables spanning a period of ten years. The analysis covers diurnal, seasonal and height variations on wind parameters. The contour maps in particular, provide a needed

reference for the spatial distribution of wind characteristics for the whole of Oman from which possible locations for the deployment of wind-based energy conversion systems may be identified. It is observed that wind speed in general is higher in the coastal regions and in particular in the south and south east of Oman. The maximum wind speeds are observed in this region in June, July and August with an average wind speed at 50 m of 6.96, 7.86 and 7.18 m/s for the three months respectively.

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